

SHEET METAL TOOLING: SELECTIVE REVIEW OF ONLINE MONITORING TRENDS

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ABSTRACT

Sheet metal forming industry has evolved over a number of decades, shaping its way from craftsmanship to technology driven processes. Even after the development of non-conventional processes for sheet metal processing, stamping remains one of the most suitable method of converting components from sheet metal for large volumes. The ever-demanding requirements from customers and the challenges forced in the tooling are of increasing quality norms and that of reducing the cost of tool built up and its service. The stamping process deviations caused due to inherent material property variation and the tool elements wear pattern continues to be the concern. The stamping process understanding of these parameters has moved through stages of laboratory experimentation to numerical analysis. Last two decades, focus has shifted towards online measurement and correction by built in sensors to automate the analytical process, thereby reducing the dependency on individual's analytical skills. The paper aims at reviewing the journey of sheet metal tooling research, creating an interest and offering a natural flow of opportunities in the field.

KEYWORDS: Sheet Metal Tooling, Online Monitoring & Closed Loop

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INTRODUCTION

Sheet metal tooling due to its high cost advantage continues to be the most demanding and accepted way of manufacturing for large volumes, even after developments of number of non-conventional metal cutting processes. The parts made out of sheet metal ranges from tiny elements in the watches to large components used in automobile or aviation. Basic process conversion from the sheet to the desired elements requires cutting and non-cutting operation. The input parameters of the overall process are sheet metal properties, the tool and the press working system. The process variations are caused due to the inherent material properties and the process conditions. Shearing operation observes the faults of burr formation, variable burnishing band or doming, dishing behaviour; whereas bending or forming operation observes spring-back variation as one of the major concerns. In draw operation, critical factor lies in obtaining the right processing window between the stages of wrinkling and tearing. The sheet metal industry has been largely dependent on the analytical skills of individuals in the tool & die making industries, and find the best possible solution at that given point. This leads to limiting conditions in accurately predicting the impact of variables on the final output and applying the correction factor. The concern of diminishing skills has been also bothering tool and die making industry over a number of decades now.

Apart from quality issues, cost of the tool has been another worry. The fact that, the cost of the tool is apportioned over the number of components produced over its entire life, tool service factor also becomes crucial. All the parameters like MQBF (Mean Quantity between failures), MQBM (Mean Quantity Between Maintenance),

tool wear, accidental damages, the speed at which tool is run, servicing cost, MTTM (Mean time to maintain), tool setting time have an impact on the cost of production. Researchers have worked in many directions to resolve these problems, but the complexity caused due to the interdependency of variables, raises a number of unanswered questions.

The stamping tools form the major assets of the industry. These assets need to be under extremely good condition to meet the requirements and suffice the needs of production lines. Effective and quality production from the tool over its entire life is one of the critical measure of tool output. The effectiveness of the tool life is achieved by routine and preventive Maintenance. Whereas due to the marginal product design or marginal tool design or erroneous work in tool running or in tool servicing may result in tool breakdowns. Abnormal conditions like misfeed, slugs coming up or double stroke causes tool damages. The damage thus caused leads to tool breakdown. The extent of breakdown in most of the cases is uncertain and adversely affects the availability of tools for production. Predictability of tools would assist in avoiding accidental damages in the tools. The production planning and control area would be in a better position to have control over minimizing inventories. The production loss cases due to non-availability of tools, causing opportunity loss, capacity loss, sales loss or customer loss would be greatly eliminated. In response to this, intelligent tooling could be the solution to reduce the need for human intervention, eliminate uncertainties, and bring in more and more predictability in the production system.

The output from the tooling depends on a number of factors. These factors include how the tool is built from design and manufacturing point of view and the way it is run during its production cycle. The quality of sheet metal product is measured and monitored in terms of dimensional accuracy, defects, surface finish, aesthetics, and so on. To achieve the ever increasing quality demands by customer continues to be the challenge. The ability of effective trial and trouble shooting of tool is part and parcel of sheet metal products. The aspects of tool wear, material property variation, conditional changes, and operator experience have great impact on the consistency in the product level quality.

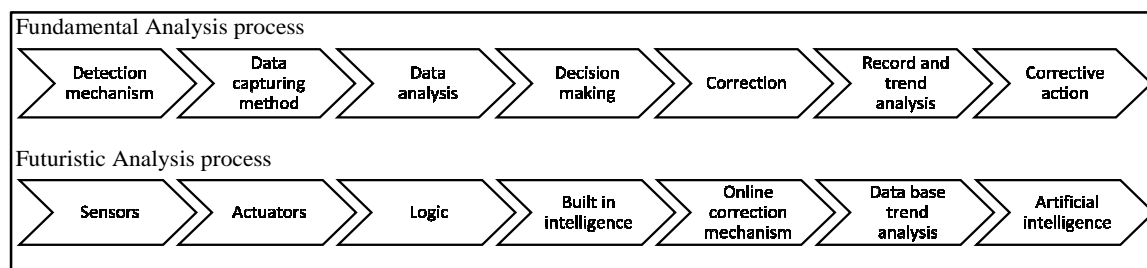


Figure 1: Analysis & Correction Approaches

The topic of sheet metal forming process advances was elaborated by Lim et al [1], in four distinct areas of quality considerations, parameter control methods, force control systems & use of sensor technology. The need for research in Cyber Physical systems in future engineering systems was described by Baheti and Gill,[2] to raise level of autonomy, functionality and reliability. Industry and academic collaboration is required in communication, computational and control disciplines to develop necessary tools, frameworks and algorithms. Leacock [3] explained the current stage of sheet metal forming and explained the need of providing practical solution to industries for incorporating the knowhow using control systems. Author suggests the developments in composition of new alloys to be made accessible to industries and the inclusion of closed loop control systems. The scenario of German tool and die making industry was analysed by Schuh et al [4], from digitalization point of view. Research focused on need for increase in digitalization in near future and also the means and avenues of the same. Entire tool life cycle aspects including, engineering, tool stage monitoring, co-ordination

with suppliers, on-line performance monitoring are briefed where digitalization can help to enhance communication, efficiency, delivery, quality.

Schuh et al [5] elaborated the need for “Smart Tooling” in future for European tool making industry. The study describes the advantages in terms of increase in productivity, avoidance of damages, improved safety and quality of the product by providing various sensors like thermal detectors, flow meters, force sensors, position sensors and solid borne sound sensors. Santos et al [6] derived a methodology for identifying strategy for being competitive in terms of technology. While doing so, concern in developed countries about workforce shortage and skills gap was mentioned. Research mentioned that to overcome this, machine tool manufacturers are promoting improvements in machine-user interface, i.e. Smart machine with self-monitoring and repairing capabilities.

The current stage of sheet metal tooling industry has just entered an era of understanding and transition into the method of bringing in intelligence in the tool. More and more development is required to explore the possibilities of using online monitoring as well as built in closed loop systems. The review presents an opportunity to understand the topic, current maturity level in the field of online monitoring systems, gamut of applications and also depicts avenues for further space in the field of sheet metal tooling advancement.

WHY ONLINE MONITORING?

Online monitoring has been the buzzword in many areas nowadays. Tooling industry is far away from application point of view. There are number of advantages of online monitoring system in tooling industry. The monitoring of marginal tool design elements would help in preventing major accidents. The hazards caused due to these mishaps would be eliminated due to early detection. The tool construction sometimes limits the access of understanding the behaviour of tool elements. The sensors placed within would get the information from such hard to access areas. The monitoring does not need to be in front of the tool. In fact, with current data capturing and communication channels, the tool monitoring is feasible from any remote location on the globe. The online data capturing helps to reduce the time and cost of the entire process. The process is most suitable in new tooling as the behaviour is unknown and computational and correctional factors can be easily applied. The process of online monitoring is also useful for older equipment's, from the point of tracking the behaviour over its entire life and useful to figure out the characteristics. This would also mean giving advance warning. The tighter online control would give quality benefits for repeatability, reproducibility enhancing the process capability as the data capturing is automatic and uninterrupted.

CLOSED LOOP SYSTEM PROGRESS IN SHEET METAL TOOLING

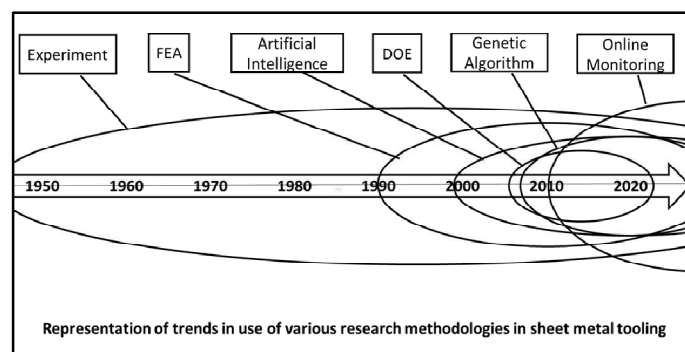


Figure 2: Use of Various Research Methodologies in Sheet Metal Tooling

The methodologies adopted for research have moved a long way with the use of latest technological advances in mechanical, electronics as well as computational techniques. The experimental testing and validation still continues to be one of the major sources of information and data collection. During the period from 1990 till 2010 use of numerical solutions for analysing the behaviour of the metal under different stress condition was dominant. Mathematical models were used to illustrate the conditions of material under shear, bend, plastic deformation phases. The researches elaborated the basic concepts of sheet metal stamping process to even micro level. Studies based on Finite element analysis, design of experiments, Genetic algorithm, Artificial Intelligence were used to capture the patterns and bring in better understanding of the process. Foremost purpose was to optimize the process. The figure 2 depicts the era of the use of technologies in recent past.

The period after 2010 has more focussed on bringing in intelligence in the system for analysis and self-correction. Number of attempts are done for establishing closed loop system which on its own, understands the problem and also corrects there itself. The systems developed for monitoring are for various stages in stamping process. These include measurement of part dimensions or it's defects, measurement of process parameters which causes the desired result of stamping and thirdly the effect of process conditions on the tool elements. The studies conducted during this period cover these aspects to a certain extent.

The evolution in the electronics field and studies in sheet metal stamping for use of these innovations have helped in tracking the behaviour of metal under stress conditions. Researchers have used variety of elements like, Piezo electric load cells, accelerometer, strain gauges, vibration sensor, temperature sensors, hall effect sensors, acoustic signal measuring sensor, triangulation laser measurement gauges, dynamometers, infrared or stereo cameras, optical microscopes for sensing the parameters. Methods like actuators, concentrators, image processors, magnetic flux transducer, amplifiers, digital/ analog converters and customized software have been used to capture the parameter. Evaluators like regression analysis, DOE, Expert system, Weibull distribution, graphical representation software, Fast Fourier transform, Matlab, customized algorithms have helped in collating and interpreting the data to help in arriving at the decision. Feedback and closed systems in few cases are used to correct or compensate for the conditions for improving the quality of parts produced.

These researches can be classified into major three categories. One by actual measurement of part, second method by monitoring the condition of tool elements and the third by process parameter measurement.

RESEARCH APPROACHES ADOPTED

External or Internal Measurement of Parts Produced

Measurement of dimensional variations caused due to the processing or the material variations fall under this category. The resultant deviations analysed are spring back effect, defects of material flows like wrinkling or tearing, thickness variation, concentricity. The issues addressed also include form errors or surface defects.

To evaluate spring back in forming process, Sun et al [7] used pressure sensors & position sensors. Programming was done using Matlab/ Simulink. Elastic recovery is tested using shock absorber fitted on a mini hydraulic press to establish the relation. Groche et al [8] used laser triangulation cameras fitted in line on a roll forming machine. The images captured are compared on Copra profile check software followed by regression analysis. A closed loop system developed to correct the side roll position which eventually compensates for the spring-back. The deviation caused due to variation in

the material properties is reduced drastically by the closed loop system. De Souza and Rolfe[9] worked on variation of five input parameters and the inter relation (multi variate) for effect on spring-back in a stamping operation. Due to material, tool, process and random variability in drawing operation it is difficult to establish cause and effect relationship. Auto-form six sigma FEM simulation is validated with multivariate probabilistic multiple noise input parameter statistical analytical model. Data was collected with DOE concept. The five parameters under consideration were yield stress, strain hardening index, sheet thickness, friction and young's modulus. Results indicating the reduced sensitivity of spring back are imperative during feasibility assessment stage to the manufacturer. All wood et al [10] claimed to be the first practical closed loop feedback system. Authors used stereo vision cameras for capturing the sheet metal behaviour in terms of deformation or spring back. Experiments on incremental sheet forming showed that, spatial impulse responses can be effectively used for online feedback control of part geometry.

Piezo quartz based dynamic force sensors with a sensitivity of 0.22mV/N embedded into the tool working surface were used by Gao et al [11] to estimate contact pressure distribution in sheet metal forming. Using thin plate spline mathematical model for bending energy function, analysis was done for decision about binder pressure for preventing defects in stamping operation. Wang et al [12] experimented on draw die for Aluminium alloy sheet using closed loop system developed with proportional Integral developer with FEM code for optimization. The purpose was to control variable blank holding pressure thereby minimizing the defects of cracking and wrinkling. Lim et al [13] worked on draw tool binder force by providing 12 hydraulic actuator sensors. Full bridge strain Sensors were provided for Punch force detection, strain gauge pressure transducers for binder force and position transducers for stroke sensing. Opal RT real time data acquisition system was set for capturing and controlling purpose. Controller was set to automatically correct the binder force based on punch force measurement. This helped in setting the right blank holding force thereby avoiding wrinkling as well as the tearing effect. Piezoelectric multiple actuators were used to control the material flow in deep drawing process by Bäume et al [14]. The material flow control has direct relation with defects like wrinkling due to reduced force or tearing, necking due to higher force. Sensor was able to locally recognize the material flow failure and the part quality was assessed by triangulation laser sensors. Endelt & Danckert [15], used non-linear finite element model & optimization scheme to control flange draw in. The diagnosis was done using forming limit diagram. The developed closed loop control algorithm and the concept of cavity pressure shimming scheme was used to control distributed & variable blank holder force to optimize the draw-in.

Experiments were conducted by Paniti and Paróczy[16] on single point incremental sheet forming with Hall effect embedded sensor in the tool. FEM simulator using Ansys was used for discretization of magnetic flux density and the force strength. Thus the correlation was established to get the online measurement of thickness of sheet. Neodymium Iron Boron Magnet was used inside cold rolled steel ball for forming Al alloy material. With the Hall effect based sensor measurement can be done on non-ferromagnetic materials only. Two bore scope stereoscopic method was used by Hamedon et al [17] to measure 3D deforming behaviour i.e. the spring back, wrinkling in shrink flanging operation and also deflection of punch. Result images from small CCD cameras of 8 mm diameter, 1.3 Megapixel resolutions drawn using image processing software and ACAD were compared with laser displacement sensors and FEA and found to have good correlation. To detect the defects in a formed article, Borsu et al, [18]used stereoscopic pair of cameras with surface modeller sensors. The data was transferred to a marking robot, which highlighted the defective area based on the feature grouping. Hao and Duncan[19] worked at Incremental sheet forming closed loop system using stereo camera image measurement and image processing algorithm set in Matlab. The purpose was to control tool trajectory for reducing the process tolerance

below ± 0.2 mm and thereby improve geometrical accuracy of the component.

To achieve stability and accuracy in multiple air bending forming method, closed loop system based on simulation by deduction method was established by Fu and Gong [20]. Z plane root locus was tracked and validated using Matlab simulation. Thus manufactured part was further measured using 3D Laser measurement system and found greater accuracies. Kot and Chan [21] experimented the use of real time visualization system of 2D laser displacement sensor in draw tool to track the deformation process. The controller was able to give a graphical representation of the deformation at time intervals. Concept of digitized die forming with multiple hemispherical matrices of punches individually controlled using hydraulic cylinders was developed by Li et al [22]. Comparison of 3D measurement of part with required model would give the deviation. The deviation was analysed using CAD/ CAM software to arrive at point by point variation & respective blank holding pressure.

Fillatreau et al [23] in their efforts to set a global control system for sheet metal forming worked on data capturing by two types of sensors. Force and acoustic sensors tracked scratches in the part surface where as geometrical variations were captured using intelligent cameras. Built in Force and Acoustic monitoring system and the algorithm based on least square method was used for data capturing and comparison. Kaupper and Merklein [24] studied the small radius bending process in AHSS material for local stiffening deformation action causing cracks. 12 HZ CCD cameras were used to capture images on light optical microscope. Further optical strain measurement and analysis helped to study failure stages, critical strain and relation with bending angles.

Approaches for Tool Item Condition Measurement

Measurement of effect on tool items due to processing has been one of the approaches in analysing the situation. This includes tool wear, tool breakage or chipping.

To monitor blanking tool condition for tool wear and breakage, Mardapittas and Au [25] developed an Expert system. This was accomplished by monitoring displacement of ram, slug return and tool breakage using optical device, punch force using piezo electric load cell, acoustic emission signal measurement during shearing and punch displacement using accelerometer. The data was captured using 12 bit digital to analog convertor. Further analysis was done using Bayesian probabilistic approach. Ubhayaratne et al [26] studied the emitted audio signal and established the correlation between the signal level and the tool wear in sheet metal progressive die. Semi blind signal extraction technique was used to counter the corrupting audio sources from the tool running on a stamping press and the nearby machinery. The study purpose was to provide low cost solution for tool condition monitoring. The signal variation given by three Microphones fitted in the tool gave clear indication of increasing wear pattern on side walls of forming edges, to identify critical point for die reconditioning.

Approaches for Process Measurement

Most commonly used and the indirect method of analysing the situation has been the process condition measurement. The conditions of material draw-in, forces, strain variation, frictional impact, thermal energy distribution, acoustic emissions, vibrations, current drawn were monitored, using various methodologies.

Mahayotsanun et al [27] developed combined system for draw-in as well as contact pressure sensors in a stamping tool for process control. Data acquisition was done by acquiring changing induced voltage from six transducers located to detect the sheet movement. Numerical analysis was done using thin plate spline surface interpolation technique.

Data captured from Piezo resistive thin film force sensors located on die flanges and die cavities was recorded using LabVIEW. Sensor system was set in draw tool by Neugebauer et al, [28] to detect the process parameters like moving edge of sheet metal, draw in to control local blank holding pressure. This was achieved by using non-contact coil sensors, piezo element sensors and laser triangulation sensors. Machine software was used to track and establish correlation to detect the process and control the process parameter. Sah et al [29] mentioned 5 different areas of work done in the sheet metal stamping process. These areas are sensor location selection, embedding the sensor in the die, evaluating the experiment, contact pressure reconstruction and designing self-energized wireless sensor. In experiments an array of dynamic piezo electric force sensor transducers were used to measure stamping pressure and draw-in maps to quantify process deviation. Finite element models were used for sensor location selection. Low viscosity hydraulic pressure system coupled with the blank displacement was used by Tommerup and Endelt [30] to control blank holding pressure. Laser displacement sensors were used for blank displacement measurement. Compact RIO real time controller used for data capturing, motor control and signal generation. Endelt et al [31] experimented on box draw tool for the control loop system to control total as well as distributed blank holder force to optimize the wrinkling or necking. The shimming scheme with fluid pressure in cavities were explained for local blank holder deformation and force control. Laser displacement sensors OMRON- ZS-LDC41 and National Instruments Compact RIO real time platform coupled with feedback algorithm was able to control the blank holder force and eliminate cracking.

Qin [32] introduced an intelligent forming tool configuration for compensating the error caused due to die deflection. This was presented as active control in a controlled manner & passive in a non-controlled manner by using a die bore variation with change in temperature and the forces to present the effect of in process error compensation. Kistler 9232A strain sensors were used by Ge et al [33] to describe the force indirectly to find the feature that would indicate the faulty condition. The trials were taken for single step blanking, multistep progressive tool in lab and onsite. The focus of the study was on defining efficient learning algorithm generating simple criteria for decision making. Wavelet packet transform or time frequency distribution was used to derive marginal energy characteristics and signal to detect abnormal conditions. Aereens et al [34] used Kistler make force dynamometers to measure three directional forces in single tool incremental sheet forming. Data amplified using multichannel charge amplifier is analysed using regression analysis to predict the force effectively. To identify the location and time of fracture occurrence in incremental sheet forming, Petek et al [35] developed a tool. Using Kistler 9239 Dynamometer mounted below the support post and Kistler 5001 charge amplifier, forming force data was measured. Reaction force in Z direction peaks at corners being the most likely position of fracture due to biaxial stretching. Data used to minimize the risk of machine damage. Neugebauer et al [36] used Piezo electric actuators in the draw tool to control blank holding pressure patterns. Data captured from four sensors was evaluated using FEM simulation and validated using experiments. Large number of force sensors were used by Havinga et al [37] in multi stage tooling to generate data & evaluate using LASSO regression method to improve the process accuracy with a decrease of 24% in Root mean square error at final stage.

Li and Bassiuny [38] used, Latent method, Morlet wavelet method, Empirical mode decomposition (EMD) and Hilbert transform (HT) method to collect information from Kistler Piezo Electric Strain sensor. The EMD and HT method with comparatively longer computing time performed better than other two on time and frequency resolution. The data was collected using an experiment on progressive draw and blanking tool. Composites made from Piezo ceramic modules and semi-finished sheet metal were used by Drossel et al [39]. The effective use of adhesive to make homogeneous composite is tested experimentally as well as by FE simulation. Experiment has thrown number of challenges in terms of

inconsistency of the intermediate layer characteristics transfer stresses to the actuator. Li et al [40] investigated the deformation mechanics in incremental sheet forming (ISF) to predict the failure to provide direction for online monitoring. The paper covered various approaches adopted for forming force prediction in different researches. The author described about surface friction and contact area for measurement prediction of forming forces. The experimental data captured using strain gauge or force sensor was used for validation or for statistical evaluation. Strain signals from Piezo electric sensors response with wavelet transform approach was established by Zhang et al [41] in his experiment to detect failure in punching process.

Ng et al [42], established the method of diagnosing the drawn part using 3D thermal energy distribution. He used the concept of “Mechanical energy is converted to thermal energy” during stamping operation. Use of Infrared camera enabled to capture images. These images were compared for strain distribution in Finite element analysis. During the research Octree carving algorithm was established in constructing the 3D thermal distribution pattern. Author suggests the method to be more convenient as compared to optical strain analysis system from lengthy time consuming grid preparation point of view.

Acoustic emission signals were used by Galy and Bernd-Arno [43] to monitor hot die forging process. Signal acquired using the data acquisition card were analysed using the program developed on LabVIEW software. The correlation was established to detect cracks, tool wear pattern. Song et al [44] also proposed a method of detecting crack in draw operation using acoustic emission. Comparative method to separate cracked & un-cracked components were developed using the condition of varying elastic energy release. The filter of frequency band was used to distinguish between two conditions. Piezoelectric sensors were also used to capture the deformation by motion sensing.

Sari et al [45] carried out basic study on online monitoring of ϕ 0.8 in 0.5 mm thick sheet punching process by reporting a potential of vibration signal. Increase in amplitude of vibration signal and the burr height was correlated to establish offline monitoring and form the means of tool condition tracking. Two uniaxial accelerometers with a sensitivity of 100mV/g used to collect data of vibration signals. After transforming to frequency domain, signal was calculated with Fast Fourier Transform. Measurement of burr height and the tool edge condition correlated with vibration signal at various stages of tool running. Increase in burr height 3.5 times was found at increase in 15 times vibration signal. Correlation between the sound signal & the force variation caused due to the wear on the micro piercing punch for monitoring the condition was established by Sari et al [46]. Shanbhag et al [47] proposed a new acoustic emission feature while monitoring the galling effect on stamping tool element. Shift in emission signal was established as a basis for condition based monitoring.

Roizard et al [48] developed a test set up to simulate tool and sheet contact condition during draw operation. Author used LVDT sensors to measure the displacement by analysing the potential difference conditions. Tool integrated five eddy current sensors based direct distance measurement system was used by Maier et al [49] for spring-back background. A laser distance sensor was set to get the triangular signal in the measuring set up. The advantage is to get the direct measurement in the tool and avoid offside measurement & the time delays caused.

Use in Defect or Accident Prevention

Most adopted form of tool monitoring from industry perspective has been in defect or accidental damage prevention. The widely used methodologies in industry are for ensuring smooth functioning of tooling for strip feeding,

avoid stripper tilting caused due to imbalance forces in operation. The methods to ensure positional accuracy of components or that of tool sliding elements helps to prevent faulty conditions.

Cheng Zhou et al, [50] developed a monitoring method to find out the missing part in multi stage progressive stamping process due to malfunction, which may cause product quality issue or may even lead to tool damages. An algorithm with the relationship plots, one of the pervasive tools for dynamic system analysis & tonnage signals was developed to set up parameters. The method is suitable to detect faults with small signal changes. Detection capability is maximised using developed algorithm.

Other Approaches

Apart from the effect on parts to be produced or the changing condition of tool elements to monitor the process, other research approaches have been for overall monitoring of tooling, communication aspects, project flow.

Heiserich et al [51] worked on sensor based tool monitoring system for counting the strokes, life of tool. Issues discussed include, tamper proof sensors for industry condition, Tool's lifetime requirement, Battery life, event log facility using EEPROM and RFID interface, Sensor-memory-battery module, tool ID, temperature constraints, Piezo electric sensor to convert vibrations into signals, illegal use of tools, real time behaviour, MAC Zigbee protocols etc. A comprehensive review about metal forming cycle was carried out by Tekkaya et al [52]. The focus was on the entire process flow from design to the final product, where final product is influenced by the material properties. The research elaborates on various methods adopted by different studies to measure the result and how feedback can be established to predict the material properties. Research emphasised on establishing a closed loop control where work piece measurement can be effectively used to give feedback for predicting and setting material properties. Zhang et al [53] elaborated data characteristics & its processing techniques to illustrate issues related to entire communication network for IoT applications. Sensors used in continuous steel casting equipment to capture data pertaining to temperature, pressure and revolving speed. CAN bus & Zig Bee based wireless networks used for data transmission. Data transmitted to the remote server by GPRS & 3G.

USE OF SENSORS

Sensor technology has started being accepted in tooling these days for detecting the change in physical stimulus and recording it in the form of signals. Sensor termed as transducer in many of the European literatures, performs the function of conversion phenomena like thermoelectric, photoelectric, electromagnetic, photo-magnetic, thermos-elastic, thermo-optic and many more. Wide range of categories of sensors are available these days. These can be classified based on measurement stimulus methods like acoustic, electric, physical, mechanical, chemical, environmental, magnetic and so on. The use of sensors in the tooling industry is limited due to the tool design limitations, lack of knowledge of sensor technology, compatible infrastructure, lack of awareness about long term cost advantage, fear of damage or contamination of sensor. Researchers have used sensors for process analysis purpose and experimental purpose.

The types of sensors as shown in Table 1 for different categories were illustrated by Polyblank et al [54]. The list would be very useful for the researchers in finding alternatives in the analytical process. The categorization is done based on measuring aspect. Displacement sensors measure the physical movement change observed. Typically, this application is most suitable for direct component or material movement measurement. Surface roughness or defect sensor identifies the surface change occurred during the material stamping process. Force sensors measures the change in force

value whereas temperature sensor measures change in temperature value caused due to change in process parameters. The measurement correlation is one of the most interesting aspects to the applicator. Microstructure or material properties sensors notices the structural change in material which helps to enhance predictability and the reliability factor.

To make the use of sensors more popular in tooling industry, one has to look at the reliability and the durability aspect of the sensor. Sensor location in the tool, its handling, its sustenance limit to withstand process condition, are essential factors to be taken care to prevent the sensors from getting damaged or malfunctioned. Typically, high vibration, high temperature, closeness to cooling lines, physical damage due to collision are the conditions in the tool which may cause sensor to get spoilt. The sensitivity of sensors to capture the desired parameter and the methodology to avoid noise conditions are vital aspects to improve the expected result.

Table 1: Sensor Categorization

Description of Sensors				
Displacement Sensor	Surface Roughness/ Defect Sensor	Force Sensor	Temperature Sensor	Microstructure/ Material Properties Sensor
Mechanical follower	Stylus scanners	Load cell	Thermocouple	Thermography
Direct induction	Optical surface measurement	Piezo electric force sensor	Bi-metallic thermometers	Magnetic particle inspection technique
Laser line triangulation	Acoustic Emissions measurement	Piezo resistive force sensor	Fibre optic temperature sensors	Eddy current inspection technique
Silhouette	Capacitance technique	Tactile sensors	Integrated circuit temperature sensors	Optical microscopy
Laser scanning	Optical microscopy		Thermistors	X-ray Diffraction
Stereovision camera	Stereo optical microscopy		Liquid crystal temperature indicators	Radiography and Tomography
Silhouette in series as part is rotated	Scanning electron microscopy		Liquid in glass thermometers	Induction spectroscopy
X-ray Tomography	Liquid penetrants technique		Piezo electric temperature sensors	Ultrasonic / acoustic method
	Inductive technique		Irreversible change of state temperature sensors	Acoustic emission
	Impedance/ skin effect technique		Thermostats	
	Friction measurement		Optical Pyrometer	

CONCLUSIONS

Use of Sensor Technology for Understanding Sheet Metal Cutting Phenomena

Current researches of online monitoring, focus mainly on sheet metal forming, spring-back, draw in behaviour and very little focus is seen pertaining to sheet metal cutting behaviour. Opportunity lies in understanding the intricacies of cutting phenomena and better predictability for design parameters with the use of sensor technology. Number of researches in the tooling industry have revolved around the understanding of the sheet metal cutting process. The understanding of

entire cutting process can be termed in three categories as described in Figure 3. Most of the decisions for optimum conditions depends on the two parameters of material & its thickness. Researchers have found that the other factors which also has an impact are, speed at which shearing operation is demanded by the customer, variations in the part geometry, force limitations as well as some of the user preferences of quality of end product or the volume requirements in reference to the quality of tool leading to tool cost variation. Based on these inputs, tool designer and the manufacturer decides the parameters like clearance between punch and die, tool material and the coating properties to withstand the load conditions and having desired resistance to abrasion. The built tool construction helps to give the rigidity and strength at required speeds, load and fatigue situations.

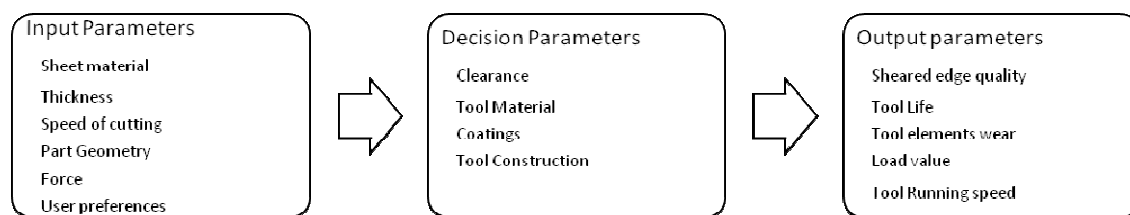


Figure 3: Sheet Metal Cutting Process Parameters

Applications of Sensors in Predictive Maintenance

There is a clear cut demarcation in tool preventive maintenance (PrM) and Tool Predictive maintenance (PdM). Preventive maintenance is carried out based on defined frequency either in terms of definite period or the volume produced. Predictive maintenance focuses on maintenance only when it is warranted for irrespective of the duration or the volumes produced. This eliminates equipment going in breakdown stage before it is due for preventive cycle as well as overdoing.

This application is suitable when it is difficult to predict the effective tool functioning due to large variation in volumes produced during each production run. This could happen due to marginal tool design, marginal product design, poor tool maintenance or poor tool run condition. In case of marginal tool design, tool goes under breakdown maintenance due to one of the critical elements. The critical element thus identified undergoes stresses and strains during its functioning and has an impact of either wear or deflection or temperature rise etc. The impact of these changes result in change in the component geometry or the mechanical properties.

In view of these situations, PdM of tooling can be looked at in 3 aspects for condition based monitoring. Refer Figure 4.

- By indirect prediction of the condition of tooling elements in terms of mechanical properties: The change in the condition of the critical tooling element can be analysed through the change in mechanical properties. And the property variation can be correlated with the changed condition of tooling element. This could be load condition getting deteriorated or the increased vibration, or the temperature rise, or even the sound level change. Established control limits synchronized with the machine will help in trigger generation and avoid the breakdown condition.
- By analysing the change in tool item condition: The continuous run of the tool generates stresses on tooling elements. These stresses cause tool element to wear or buckle or cause fatigue failure. The correlation of the condition of these changes in tool element with the breakage limit will help in establishing the control limit and the trigger for stoppage of tool before it goes in to breakdown.

- By measurement of component condition: Due to the change in the tool item condition, certain changed condition of the component can be monitored. The changed condition like dimensional change or increased burr level, dishing level or any quality attribute caused due to variation in tool item condition becomes criteria for monitoring and setting up a threshold limit for stoppage for necessary reconditioning of tooling element.

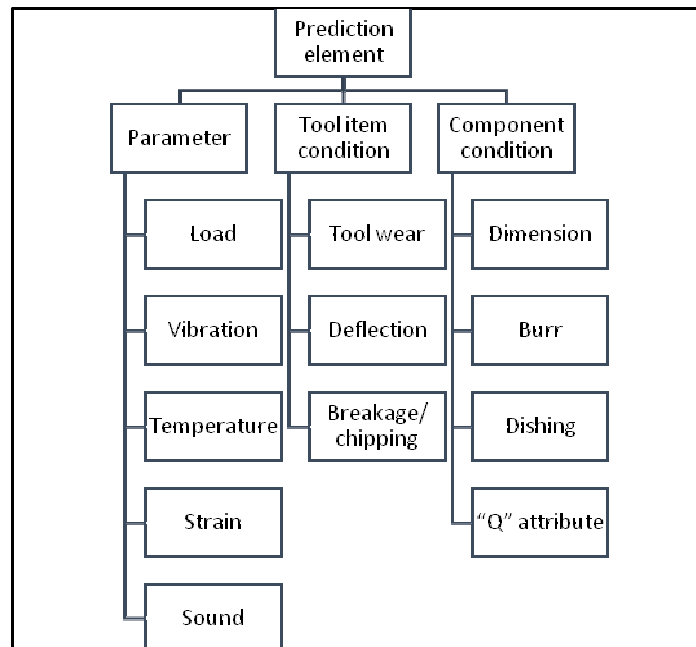


Figure 4: Approaches for PdM

Thus, PdM offers enormous opportunities in tooling industry to set up online monitoring to prevent tool breakdown as well as efficient usage of tool. Sensors could be of good use in this regard. The major steps that will be needed for effective implementation of PdM are that of identifying critical element of the tool, designing a built in sensor mechanism, capturing of data for the specific condition, establishing correlation with the identified critical tool element or component quality parameter, setting up a control limit and developing an online control mechanism for early detection.

Efficiency Measurement

The effective use of shot counters is carried out today for efficiency measurement of tooling. The mechanical counters with digital display are used in the moulds to count the production volumes. Connectivity using networking is able to capture the production data throughout the globe. User friendly softwares are developed for data mining and establishing the methodology and logistics for efficient preventive maintenance throughout its life. The constraint still lies in developing the cost effective solution of physical counters to withstand stringent conditions of vibrations, communication channel to prevent data loss for tools running at high speeds and also the capability to withstand in the moulds running at high temperatures. Power management for the counter to remain live throughout the life of tool is one of the important essentials in the making. Solutions to these aspects would ensure complete solution for efficiency measurement of tooling.

Establish Process Capability Monitoring and Control

Use of sensor for prompt recognition of defect and mechanism to online correct the fault condition is one of the important area available to explore further. The development with backing of statistical measurement tools would not only

control the final product quality but also build assurance in the system. Further focus can be established for measuring how close a process is running with respect to its specification limits (C_p) and also the effect of non-centred distribution (C_{pK}). This is illustrated by Neugebauer et al [28] by an example of narrow process window between wrinkles and cracks in draw operation.

Evaluate Effect on Tool Steel Properties

Due to the continuous operation, change takes place in the tool steel material. The change thus caused could be on the external surface or that in internal structure. External surface changes are attributed as wear, scratch or crack formation category. In some cases, these alterations, even lead to higher surface adhesion. Internal structural change could be work hardening, surface hardening or built in magnetism. These alterations thus caused has an impact on tool smooth functioning. Like in case of progressive tools, magnetism may lead to coil feeding, slug jamming issues. Work hardening may cause brittleness resulting in cracks formation. These are some of the aspects which can be explored for monitoring using online measurement system, which would help in better analysis and remedial measures.

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